EXTRA DIMENSIONS

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LECTURE 4

MIXING OF ZERO AND KK MODES FOR W, Z VIA HIGGS VEV

Zero and KK modes for $W_{i=1,2,3}$ and B (hypercharge) defined with $v = 0$ (no kinetic/mass mixing)

$v \neq 0$: mass mixing for zero-modes (as in SM) $\rightarrow$

Define $Z_\mu^{(0)}$, $A_\mu^{(0)}$ as combinations of $W_3^{(0)}$ and $B^{(0)}$: diagonalize 0-mode mass mixing (as in SM)

$g_{W^{(0)}} = g_{5\;2}/\sqrt{2\pi R + r}$, $g_{Z^{(0)}} = g_{5\;Z}/\sqrt{2\pi R + r}$...

$(g^2_{5\;Z} = g^2_{5\;2} + g'^{\,2}_5)$

Define $Z^{(n)}$ and $A^{(n)}$ using same (0-mode) mixing angles

$A_\mu^{(n)}$ does not couple to Higgs (like zero-mode)

- Zero and KK modes of W mix via Higgs vev localized at $y = \pi R$ (similarly for Z): mass eigenstates are mixtures

diagonalize 2×2 mass matrix (zero and 1 KK mode) for simplicity (homework 3)

2. SHIFT IN COUPLING TO Z

Shift in coupling of fermion at $y = 0$ from pure

zero-mode coupling,

due to (small) KK Z component of SM Z:

$g_Z = g_{Z^{(0)}} + \delta g_Z$

Estimate via mass insertion diagrams

(valid for $v \times$ couplings $\ll m_{KK}$):

$\delta g_Z \sim g^2_{Z^{(0)}} v^2 / m^2_{KK}$,

$\rightarrow$ *no* enhancement in δg_Z for large brane kinetic

terms $(r/R \gg 1)$

(enhancement at Higgs-KK Z vertex cancels

suppression at fermion-KK Z vertex)

- Agrees with SM prediction at $\sim 0.1\%$ level $\rightarrow$

  $m_{KK} \gtrsim$ a few TeV

3. ρ PARAMETER

Shift in W mass from pure zero-mode mass (also for Z):

$$M_W^2 = M_{W^{(0)}}^2 + \delta M_W^2 \tag{1}$$

$$M_{W^{(0)}}^2 = \frac{1}{4} g_{W^{(0)}}^2 v^2 \tag{2}$$

$$\frac{\delta M_W^2}{M_{W^{(0)}}^2} \sim g_{W^{(0)}}^2 \frac{v^2}{m_{KK}^2} \frac{r}{R} \tag{3}$$

What about

$$\rho = \frac{M_W^2}{M_Z^2} \times \frac{g_Z^2}{g_2^2} \, ? \tag{4}$$

$\rho = 1$ in SM (tree-level); $\Delta\rho_{expt.} = \rho_{expt.} - 1 \sim 10^{-3}$

Subtlety due to couplings modified from pure zero-mode:

$g_Z = g_{Z^{(0)}} + \delta g_Z$, but δg_Z not enhanced by $r/R \gg 1$

$\rightarrow$ set $g_Z \approx g_{Z^{(0)}}$ in $\Delta\rho$

$$\delta\rho \equiv \rho - 1 \sim \left(g_{Z^{(0)}}^2 - g_{W^{(0)}}^2 \right) \frac{v^2}{m_{KK}^2} \times \frac{r}{R} \tag{5}$$

- $\Delta\rho$ enhanced by large brane kinetic terms $\rightarrow$

  $m_{KK} \gtrsim 10$ TeV for $r/R \sim 10$

CUSTODIAL ISOSPIN IN SM

Higgs potential, $V(|H|)$ with

$$H = (h_1, h_2, h_3, h_4) \tag{6}$$

has enhanced $SO(4) \approx SU(2)_L \times SU(2)_R$ symmetry

$\to SO(3) \approx SU(2)_{\text{cust.}}$ by

$$\langle H \rangle = (0, 0, 0, v) \tag{7}$$

$\longrightarrow$ equal mass for $W^L_{i=1,2,3}$

W^L_3 only mixes with B (no mixing for $W^\pm_L$)

$\to M_Z^2 = 1/4\ v^2 \left(g_2^2 + {g'}^2 \right) \neq M_W^2 = 1/4\ v^2 g_2^2$

- Factor of g_Z^2/g_2^2 in definition $\rho = M_W^2/M_Z^2\ g_Z^2/g_2^2$ takes this "violation of custodial symmetry" into account

CUSTODIAL ISOSPIN VIOLATION IN $5D$

$\Delta\rho$ from KK $\propto \left(g^2_{Z^{(0)}} - g^2_{W^{(0)}} \sim g^2_{B^{(0)}}\right)$ as in SM

- *Additional* mixing (due to KK modes):

  $W^{(0)}_{L\,3} - B^{(n)}$ (only in neutral sector)

  no charged counterpart

$SU(2)_L \times U(1)_Y$ gauged in $5D \rightarrow$

KK's only for $W^{3\,\pm}_L$ and B

new effect not taken into account by factor of g^2_Z/g^2_2

in definition of ρ

$W^{(0)}_{L\,3} - B^{(n)}$ mass term

$\sim g_{W^{(0)}} g'_5 \times f_n(\pi R) v^2 \sim g_{W^{(0)}} g_{B^{(0)}} v^2 \sqrt{r/R}$

$\rightarrow$ enhanced for large brane terms!

$W^{(0)}_{L\,3} - W^{(n)}_{L\,3}$ mixing *does* have counterpart in charged

sector

CUSTODIAL ISOSPIN SYMMETRY IN $5D$

Need extra KK modes to partner $B^{(n)}$:

promote to a triplet

- Restore custodial isospin by $SU(2)_L \times SU(2)_R$

  gauged in $5D$ (hep-ph/0308036)

$SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ for fermion hypercharges:

$Y = T_{3R} + (B - L)/2$

$T_{3R} = \pm 1/2$ for $(u, d)_R$ and $(\nu, e)_R$,

$B - L = 1/3, -1$ for q, l (check)

KK $U(1)_{B-L}$ do not couple to Higgs: only KK $W^{3\,\pm}_{L,R}$

KK exchanges respect custodial isospin

(same in charged and neutral channels)

BREAKING BY LARGE MASS ON BOUNDARY $\equiv$ BOUNDARY CONDITION

Break $SU(2)_R \times U(1)_{B-L} \rightarrow U(1)_Y$: no zero-modes for $W_R^{\pm}$ and extra $U(1)$ (combination of $U(1)_R$ and $U(1)_{B-L}$ orthogonal to $U(1)_Y$)

- Breaking must approximately preserve degeneracy – of mass and coupling (to Higgs) – for (at least light)

  $W_R^{\pm}$ vs. W_R^3 modes to protect $\Delta\rho$

For large brane kinetic terms ($r/R \gg 1$),

KK's localized near $y = \pi R \rightarrow$

break on $y = 0$ brane, degeneracy not affected by breaking

Large mass term for $W_R^{\pm}$, extra $U(1)$ at $y = 0$ (from scalar vev) $\equiv$ requiring vanishing at $y = 0$

(odd/Dirichlet boundary condition: section 3.3 of hep-ph/0404096)

SIGNALS (I)

- Coupling of KK gluon to top enhanced,
  to light fermions suppressed

Real production of gauge KK

Broad resonance decaying into top pairs

challenge to distinguish from SM background:

use spin-correlation (spin-1 for KK gluon vs. not for SM t-channel gluon exchange) or

dominantly decays to *R*H top (due to $Z \rightarrow \bar{b}b$)

- Distinguish from SUSY: no missing energy $+$ top special

SIGNALS (II)

Virtual exchange of gauge KK

1. $\bar{t}tZ$ shifted compared to $\bar{e}eZ$:

   measure at ILC

2. Flavor violating coupling to KK $Z \rightarrow$

   $t \rightarrow cZ$ (at LHC)